DEMONSTRATION OF SYNCHRONIZATION BETWEEN TWO GEOSYNCHRONOUS SATELLITES WITHOUT GROUND INTERVENTION

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Abstract

In early 1996 Milstar became the first geosynchronous satellite system to employ crosslinks for synchronization and syntonization. At that time, the crystal oscillator onboard DFS-1, the first Milstar satellite, had its time and frequency tied (i.e., slaved) to the rubidium (Rb) atomic clock carried onboard DFS-2, the second Milstar satellite. The slaving of DFS-1 to DFS-2 was accomplished without ground intervention. All timing information required by the slaving algorithm was obtained through the DFS-1 to DFS-2 satellite crosslink. In this paper we discuss the drift and Allan variance of the two satellite clocks when operating independently, and show that both clocks are performing well. Additionally, we present ground station measurements of DFS-1 and DFS-2 time offsets that demonstrate satellite synchronization to better than 150 ns without ground intervention.

1 INTRODUCTION

Satellite navigation and communication often require fairly precise synchronization and syntonization among spacecraft clocks. In the traditional method for achieving synchronization, a ground station makes time-offset measurements to the various spacecraft clocks, and then updates the time and frequency of each satellite as needed. Though straightforward in its implementation, disadvantages to the traditional approach include the large workload placed on the ground station, the need to have several ground stations to view satellites in different orbital locations, and unaccounted-for delays in atmospheric propagation.

The Milstar communications system has chosen a different method for spacecraft synchronization and syntonization. Milstar's mission is to provide secure antijam communication capabilities for United States Department of Defense operations into the next century[1], and in order to accomplish that task Milstar employs precise timekeeping on its satellites and at its ground control stations.[2] A Milstar ground station makes time-offset measurements to an in-view

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geosynchronous satellite, which for this illustrative discussion we will call the Master, and as a result of information passed along the satellite crosslinks, other satellites in the constellation (i.e., Slaves) autonomously synchronize and syntonize themselves to the Master. Since the ground station only needs to steer the time and frequency of a single satellite, its workload, and hence the timekeeping-related operational costs of the system, are held to a minimum. Moreover, since synchronization among the satellites is accomplished without transmission through the ionosphere, atmospheric propagation delays cannot perturb the synchronization among spacecraft clocks.

The first of six Milstar satellites, DFS-1, was launched on 7 February 1994, while DFS-2, the second Milstar satellite, was launched on 6 November 1995. Each satellite carries a set of precise clocks: DFS-1 carries crystal oscillators, while DFS-2 carries rubidium (Rb) atomic clocks.[3] The ground stations maintain precise time with cesium (Cs) atomic clocks. Following the launch of the second Milstar satellite, crosslinks between DFS-2 and DFS-1 were activated and DFS-1's time and frequency was slaved to DFS-2. In the slaving procedure, DFS-1 uses satellite crosslink information to rapidly correct its time so as to stay synchronized to DFS-2, and to periodically correct its oscillator frequency. DFS-2 is synchronized to UTC by a ground station that periodically collects timing information from the satellite, and after a number of days commands time and frequency adjustments to the DFS-2 satellite clock.[4] Timekeeping data can be collected by ground stations for both satellites, and is archived along with any commanded time and frequency corrections. Using the archived data we have been able to reconstruct "raw" time offsets for the DFS-1 and DFS-2 clocks, that is, the time offsets that would have been observed on the ground had the ground station made no time or frequency corrections to the satellite clocks. In the following we will show that an Allan variance analysis of these raw time offsets indicates that each clock is performing well, and that when crosslink synchronization is initiated DFS-1 achieves a 150 ns or better synchronization to DFS-2 without assistance from the ground.

2 DFS-1 AND DFS-2 CLOCK PERMORMANCE

Deterministic Timekeeping Variations

The reconstructed raw time-offset measurements of DFS-1 and DFS-2 are displayed by the thick lines in Figs. 1a and 1b respectively; thin lines show quadratic fits to the data. (In both figures, initial time and frequency offsets were subtracted from the data sets to better display the quadratic variation of time offset.) For DFS-1, the quadratic fit yields a $+9.8\times10^{-13}$/day drift rate, which is quite good for a crystal oscillator clock.[5] Moreover, DFS-1 has exhibited this same drift rate since October 1994. Analysis of the data presented in Figure 1b indicates that DFS-2 has a -1.5×10^{-12}/day drift rate. Though the magnitude of this drift rate is a bit larger than that of the crystal oscillator clock, it is nonetheless consistent with pre-launch expectations for the DFS-2 Rb atomic clock at this point in its operating life. With continued operation, the slowly varying frequency drift rate should drop well below the 10^{-12}/day level and should eventually become constant. The deviation of the raw time-offset data from the quadratic for the early part of DFS-2's time-offset history is a consequence of the atomic clock's warm-up behavior.[6] The important point to note from Figure 1 for future discussion is that the aging rate of the DFS-1 clock is distinctly different from that of the DFS-2 clock.

Allan Variance

Taking the difference between the raw time-offset measurements and the quadratic fit, time-offset residuals may be computed. Computation of the Allan variance for the residuals requires

uniformly spaced measurements of oscillator frequency. Since the archived ground station measurements are not separated by a constant interval, interpolation of the data is necessary in order to generate a history of fractional frequency fluctuations amenable to Allan variance analysis. Vernotte et al.[7] have shown that a Linear-Interpolation (LI) procedure is a viable strategy for interpolating unevenly spaced time error data, and we have employed their approach here.

Figure 2 shows the resulting Allan standard deviation, $\sigma_y(\tau)$, versus τ for the DFS-1 crystal oscillator and the DFS-2 Rb atomic clock. Dashed lines correspond to estimates of the Allan standard deviation based on a simple model: satellite to ground-station time-transfer noise dominates the Allan variance for τ less than 10,000 seconds, while random-walk frequency noise dominates $\sigma_y(\tau)$ for longer averaging times. (Satellite to ground-station time-transfer noise is associated with randomly varying delays at the transmitter and receiver.) For the crystal oscillator the long-term Allan standard deviation is well modeled by $\sigma_y(\tau) = 1.6\times10^{-14}\,\tau^{1/2}$, a value consistent with a high-performance crystal oscillator.[8] For the Rb atomic clock the long-term Allan standard deviation is well modeled by $\sigma_y(\tau) = 2.2\times10^{-15}\tau^{1/2}$, again a value consistent with a well-functioning device.[9]

3 AUTONOMOUS SYNCHRONIZATION

As noted in the Introduction, following the launch of DFS-2 the DFS-1 satellite became a slave to DFS-2, and therefore tied its crystal oscillator to the DFS-2 atomic clock using crosslink timing information. Given the archived data of DFS-1's time offset during the slaving period, along with ground station corrections to DFS-2 and DFS-1, it is possible to reconstruct the timekeeping behavior of DFS-1 while it was slaved to DFS-2. This is shown in Figure 3, where the black data points correspond to DFS-1 raw time-offset measurements, and the curve is a quadratic least squares fit to the data. (We note for future reference that DFS-1 slaving to DFS-2 was deactivated for several days during this period.) The fit yields a -2.3×10^{-12}/day fractional frequency drift rate. This is to be compared with the DFS-1 crystal oscillator's intrinsic drift rate of $+9.8\times10^{-13}$/day. The -3×10^{-12}/day change observed in DFS-1 drift is due to the fact that during this period DFS-1 maintained tight synchronization and syntonization to the DFS-2 Rb atomic clock, which had a negative drift rate. We further note that the discrepancy between DFS-1's (apparent) -2.3×10^{-12}/day drift rate and DFS-2's -1.5×10^{-12}/day drift rate is a consequence of the few days during this period when slaving was turned off. If an attempt is made to account for those few days, the DFS-1 and DFS-2 drift rates become nearly identical.

An estimate of the level of synchronization between DFS-1 and DFS-2 may be obtained from raw time-offset measurements made to both satellites by a single ground station. As illustrated in Figure 4 this occurred in early February 1996. On 8 February 1996 a ground station commanded a time and frequency correction to the DFS-2 atomic clock, and then began making time-offset measurements to DFS-1 (filled circles in the figure). Then, on 9 February 1996 the same ground station began making time-offset measurements to DFS-2 (open circles in the figure). The solid line is a quadratic fit to all the data, clearly indicating that the ground station synchronized DFS-2. DFS-1 was not corrected by any ground command, but rather by autonomous crosslink synchronization to DFS-2. Based on the deterministic and stochastic variations of the crystal oscillator's fractional frequency, and the fact that DFS-1 received its last correction from the ground on 4 February, DFS-1's time offset should have been appreciable on the scale of Figure 4 (i.e., at the 1-σ level somewhere within $\sim\pm3$ μs). However, as a consequence of crosslink synchronization to DFS-2, DFS-1's time offset was near zero.

Computing the standard deviation of time-offset residuals from the quadratic regression line, we have $\sigma_{DFS-2} = 141$ ns and $\sigma_{DFS-1} = 207$ ns. These variations about the regression line are a consequence of: 1) satellite to ground-station time-transfer noise, 2) diurnal oscillations due to the satellite clocks' temperature sensitivities, and 3) crystal oscillator and atomic clock noise processes. Additionally, the DFS-1 variations must include the residuals associated with the slaving process. Consequently, we can obtain an upper bound on the slaving process's error in synchronizing DFS-1 to DFS-2 by combining these two standard deviation values:

$$\sigma_{slaving} \leq \sqrt{\sigma^2_{DFS-1} - \sigma^2_{DFS-2}} = 152 \text{ ns} \tag{1}$$

Thus, the data demonstrate that the two spacecraft were synchronized to within ±150 ns, *independent of ground-station intervention.*

4 CONCLUSIONS AND SUMMARY

As satellite navigation and communication applications increase, greater emphasis will be placed on synchronizing spacecraft clocks independent of ground intervention. In part, this situation will be motivated by a desire: 1) to reduce the workload at mission control ground stations and reduce system operating costs, 2) to control a geosynchronous constellation from a single location, and 3) to reduce unaccounted-for delays in atmospheric propagation. Milstar is the first satellite system to employ crosslink synchronization for geosynchronous spacecraft, and here we have demonstrated the efficacy of that method. Specifically, our results show that crosslink synchronization has allowed DFS-1 and DFS-2 to achieve a 150 ns (or better) level of synchronization without intervention from the ground.

8 REFERENCES

[1] J. Fawcette 1983, *"Milstar: hotline in the sky,"* **High Technology**, November 1983, pp. 62-67; M. Dornheim 1992, *"Milstar 2 brings new program role,"* **Aviation Week & Space Technology**, 16 November 1992, pp. 63-64.

[2] J.C. Camparo, and R.P. Frueholz 1995, *"Monte Carlo simulations of precise timekeeping in the Milstar communications satellite system,"* Proceedings of the 26th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 6-8 December 1994, Reston, Virginia, USA (NASA CP-3302) pp. 291-304.

[3] J.C. Camparo, and R.P. Frueholz 1995, *"Timekeeping performance of the Milstar DFS-1 satellite: October-December 1994,"* Aerospace Report No. TOR-95(5404)-4, 1 May 1995.

[4] J.C. Camparo, and R.P. Frueholz 1994, *"Precise timekeeping in Milstar: the Aerospace Corporation's Monte Carlo simulations,"* Aerospace Report No. TOR-94(4404)-5, 15 May 1994.

[5] L.J. Rueger, J.R. Norton, and P.T. Lasewicz 1992, *"Long-term performance of precision crystal oscillators in a near-earth orbital environment,"* Proceedings of the 1992 IEEE International Frequency Control Symposium, 27-29 May 1992, Hershey, Pennsylvania, USA, pp. 465-469.

[6] C.H. Volk, and R.P. Frueholz 1985, *"The role of long-term lamp fluctuations in the random-walk of frequency behavior of the rubidium frequency standard: A case study,"* **Journal of Applied Physics, 57**, 980; H. Bethke, D. Ringer, and M. Van Melle 1985, *"Rubidium and cesium frequency standards status and performance of the GPS program,"* Proceedings of the 16th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 27-29 November 1984, Greenbelt, Maryland, USA, pp. 127-141.

[7] F. Vernotte, G. Zalamansky, and E. Lantz 1994, *"Noise and drift analysis of non-equally spaced timing data,"* Proceedings of the 25th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting 29 November-2 December 1993 (NASA CP-3267), pp. 379-388.

[8] M.B. Bloch, J.C. Ho, C.S. Stone, A. Syed, and F.L. Walls 1989, *"Stability of high quality quartz crystal oscillators: an update,"* Proceedings of the 43rd Annual Symposium on Frequency Control, 31 May-2 June 1989, Denver, Colorado, USA (IEEE), pp. 80-84.

[9] H. Hellwig 1979, *"Microwave time and frequency standards,"* **Radio Science 14**, 561.

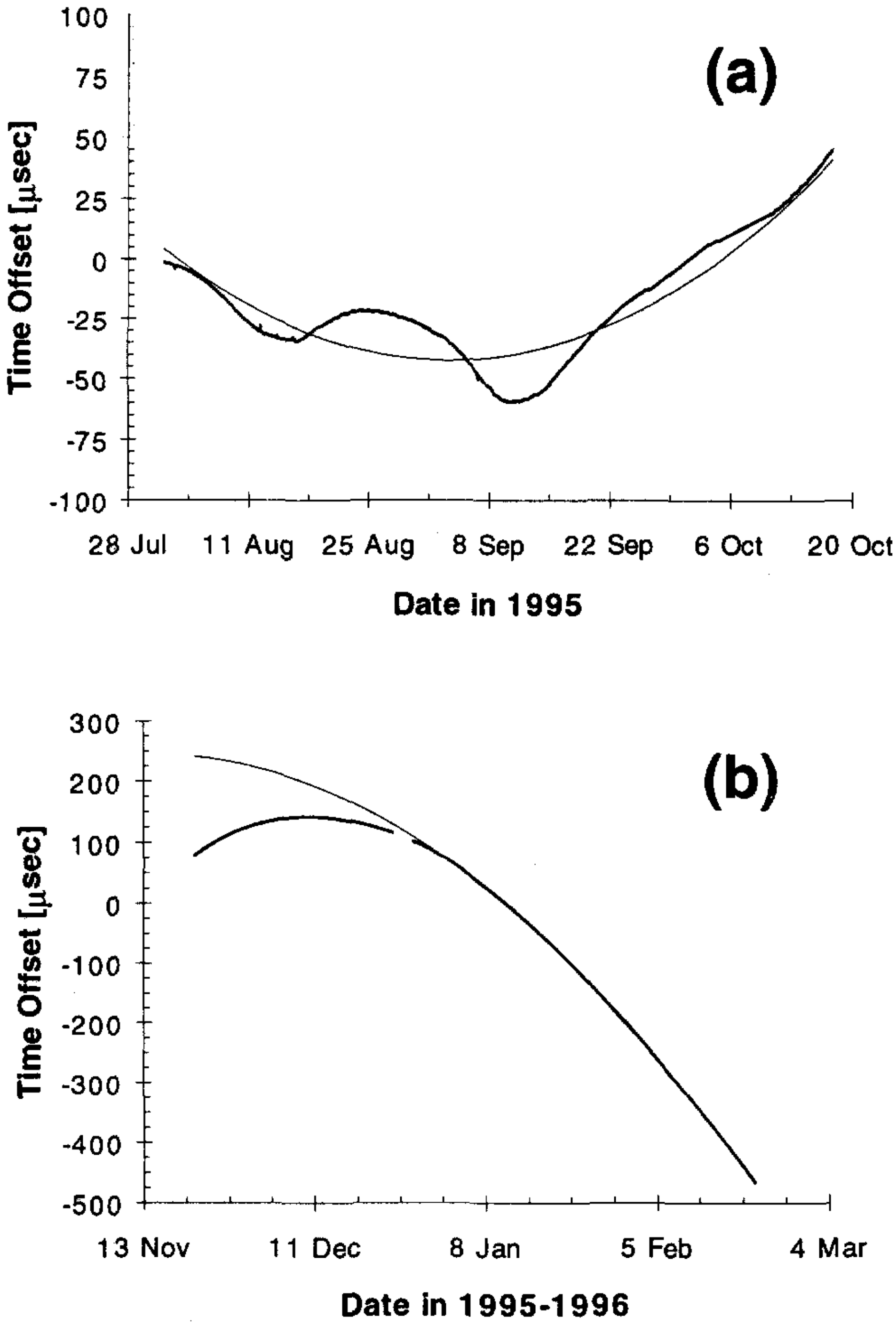

Figure 1: (a) Raw time-offset history of the crystal oscillator onboard DFS-1 (thick line). (b) Raw time-offset history of the Rb atomic clock onboard DFS-2 (thick line). Thin lines correspond to least squares quadratic fits to the data, and minor divisions of the abscissa correspond to seven day intervals.

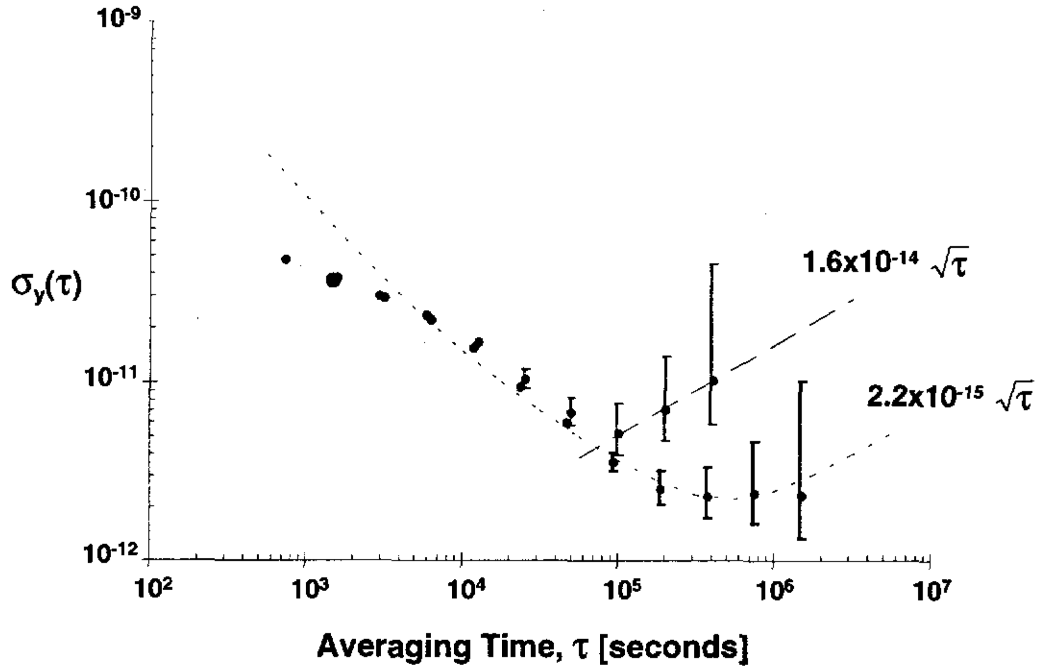

Figure 2: Allan standard deviation, $\sigma_y(\tau)$, versus averaging time, τ, for the DFS-1 crystal oscillator (gray) and the DFS-2 Rb atomic clock (black). The short dashed curve is the anticipated $\sigma_y(\tau)$ based on satellite to ground-station time-transfer noise and the Rb clock's random-walk of frequency noise. The long dashed line corresponds to the crystal oscillator's random-walk noise.

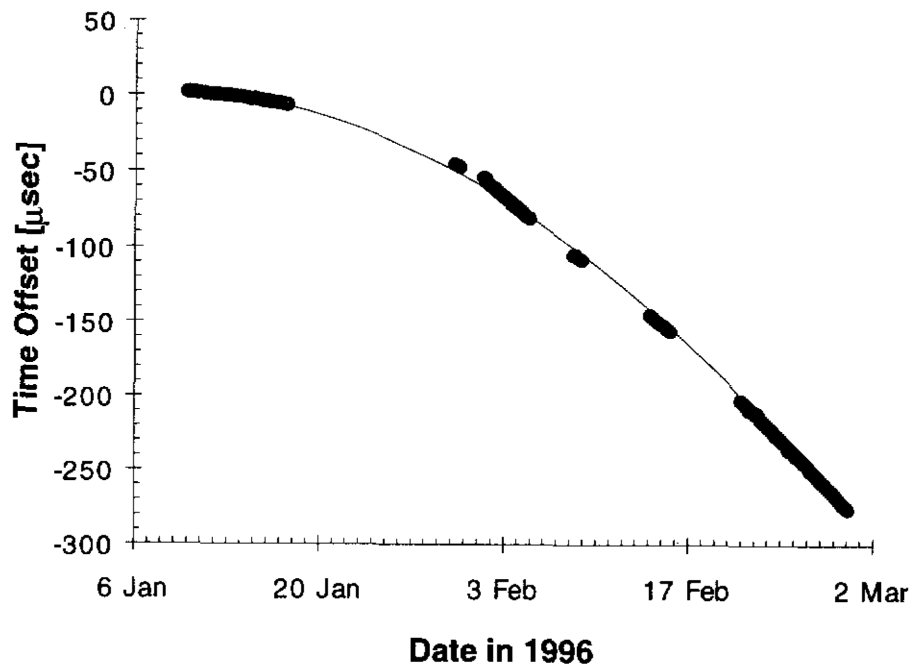

Figure 3: Raw time-offset of the DFS-1 crystal oscillator (black circles) while it was slaved to the DFS-2 Rb atomic clock. The thin curve is a least squares quadratic fit to the data.

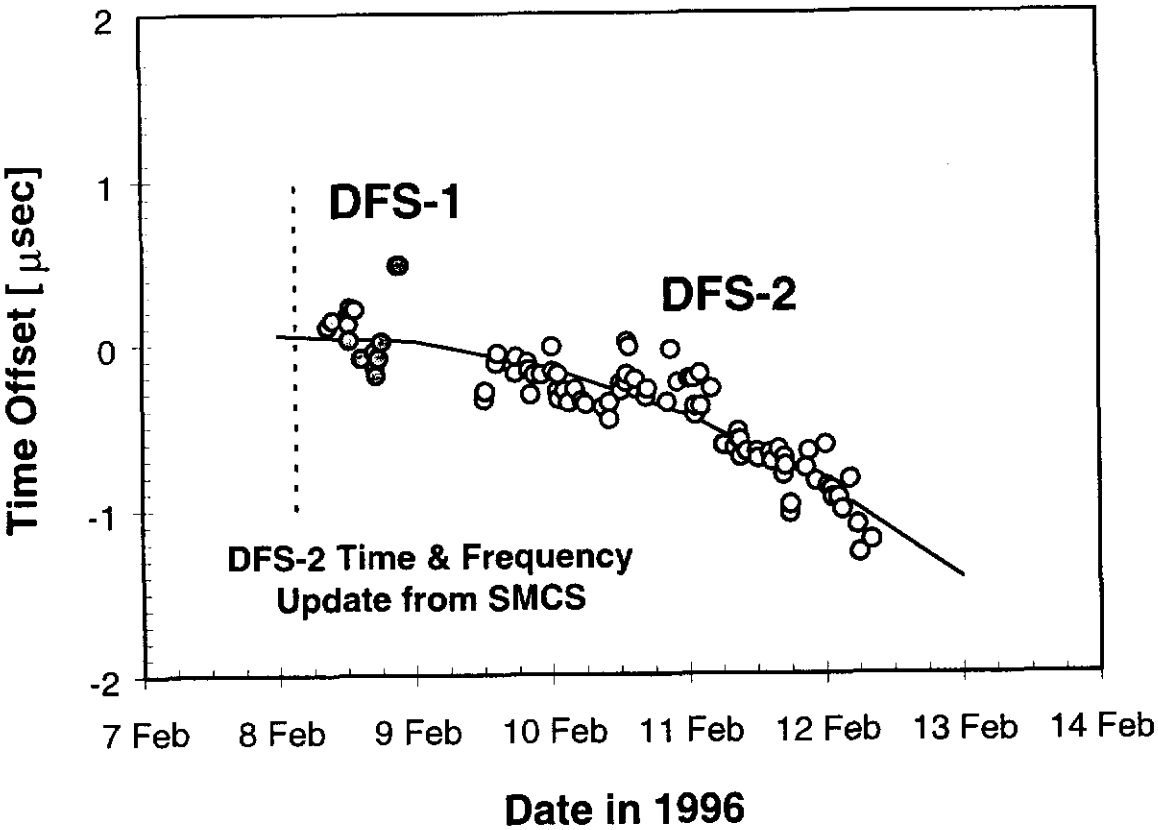

Figure 4: Raw time-offset measurements of the DFS-1 crystal (gray) and the DFS-2 Rb atomic clock (open) by the same ground-station. The dashed line indicates the date when the ground-station made a time and frequency correction to the DFS-2 Rb atomic clock, and the solid line is a quadratic fit to all the data. During this period, the last ground-station time and frequency correction to DFS-1 occurred on 4 February.

Questions and Answers

BOYD MOORE (KAMAN SCIENCES CORP.): How far apart were these satellites?

JAMES CAMPARO: They were both located over the Continental United States when these measurements were taken.

JAMES DeYOUNG (USNO): I don't remember the other two Milstar satellites; did they get a budget cut?

JAMES CAMPARO: No, no. The constellation is not complete.

MICHAEL GARVEY (FREQUENCY AND TIME SYSTEMS, INC.): Do you know what the nature of the locking algorithm is? Is this a frequency lock?

JAMES CAMPARO: One way that that can be accomplished is that the satellites can send out a message to each other. They agree on a time that they're going to send out a message. This clock sends out a message at 1:00, and it receives the message from the other satellite sometime later. And now it's got a differential time of arrival. It will then pass that differential time of arrival back sometime later, call it 1:10. And with that information, this satellite knows its own differential time of arrival at 1:00. It's gotten information on what the other satellite's differential time of arrival at 1:00; and it can use that information; it can take the difference between the two to estimate the time offset between the clocks without knowing the range, except for the Sagnac effect.

MICHAEL GARVEY: From your comments, it's a phase-lock loop essentially, since they're locking to time.

JAMES CAMPARO: Yes.

MARTIN BLOCH (FEI CORP.): Time lock!